African Journal of Advanced Pure and Applied Sciences (AJAPAS)
Online ISSN: 2957-644X
Volume 5, Issue 2, 2026
Page No: 200-205
Website: https://aaasjournals.com/index.php/ajapas/index
ISI 2025: 1.126 SJIFactor 2024: 6.752 معامل التأثير العربي: 1.62

Surface Modification of Copper Alloy by Nd: YAG Laser: An Analytical Study on Roughness Evolution and Wettability

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تعديل سطح سبيكة النحاس باستخدام ليزرالنيوديميوم ياك: دراسة تحليلية حول تطور الخشونة وقابلية التبلل

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Received: March 12, 2026 | Accepted: May 17, 2026 | Published: May 30, 2026

Abstract:
Copper alloys are frequently used in a variety of industrial applications due to their high thermal and electrical conductivity. However, precise control over surface properties is required for improved performance in heat transmission, electronics, and corrosion resistance. In this study, the impact of laser treatment on a copper alloy surface irradiated by a pulsed Nd: YAG laser was investigated. The effects of laser power (10, 20, 30 W), scanning speed (100, 500, 1000 mm/s), and pulse repetition rate (10, 20, 30 kHz) on surface roughness and wettability were systematically explored. The experimental results were analyzed using the Taguchi method, which revealed that pulse repetition rate is the most critical parameter in controlling both surface roughness and wettability.

Keywords: Nd: YAG laser, Surface roughness, Wettability, Copper alloy, Taguchi method.

الملخص
تُعد سبائك النحاس من المواد المستخدمة بكثرة في مجموعة متنوعة من التطبيقات الصناعية بفضل موصليتها الحرارية والكهربائية العالية. ومع ذلك، يتطلب تحسين الأداء في مجالات انتقال الحرارة، والإلكترونيات، ومقاومة التآكل تحكماً دقيقاً في خصائص السطح. تناولت هذه الدراسة استقصاء تأثير المعالجة بالليزر على سطح سبيكة نحاس تم تعريضها لنبضات ليزر النيوديميوم ياك. وقد تم استكشاف تأثيرات كل من قدرة الليزر (10، 20، 30 واط)، وسرعة المسح (100، 500، 1000 مم/ثانية)، ومعدل تكرار النبضات (10، 20، 30 كيلو هرتز) على خشونة السطح والتبلل بشكل منهجي. أظهر تحليل النتائج التجريبية باستخدام طريقة تاغوتشي أن معدل تكرار النبضات هو العامل الأكثر حسمًا في التحكم بكل من خشونة السطح وقابلية التبلل.

الكلمات المفتاحية: ليزر النيوديميوم ياك، خشونة السطح، التبلل، سبيكة النحاس، طريقة تاقوشي.

Introduction

Laser technology has become an indispensable tool over the past three decades, with applications spanning a wide range of scientific and industrial fields [1]. Its evolution has led to significant advancements in high-precision manufacturing, particularly in the laser surface modification of metallic alloys [2–6]. Among these applications, laser texturing has emerged as an effective method due to its process flexibility, high efficiency, and environmental sustainability [7–10]. By precisely controlling the laser–material interaction, it is possible to engineer surface morphology to meet specific functional requirements, such as enhanced thermal management and the precise tuning of surface wettability. As a non-conventional manufacturing process, laser beam machining offers remarkable versatility, allowing for the creation of intricate surface micro-textures with high precision and repeatability. Consequently, laser processing has extended beyond traditional cleaning to become a sophisticated approach for tailoring the functional properties of materials. This is achieved through controlled nano and microscale texturing, which enhances interfacial adhesion and improves bonding performance [11–13].

Numerous studies have indicated that laser texturing induces significant changes in surface morphology by producing specific microstructures that alter both wettability and roughness. Beyond topographical alterations, laser irradiation can also trigger chemical modifications, such as surface oxidation [14–16]. Among the materials benefiting from these advancements, copper alloys are of particular interest due to their widespread use in thermal management and electronic packaging. However, the high optical reflectivity and thermal conductivity of copper pose significant challenges for achieving precise surface modification, necessitating a systematic optimization of laser parameters [17–18]. Recent investigations have demonstrated that laser surface texturing enables the precise tuning of copper wettability, spanning from super hydrophilic to superhydrophobic regimes, through the controlled modification of surface morphology and chemistry [19–20].

The wettability of copper alloys is a dual-driven process governed by hierarchical structural modifications and surface chemical evolution [21]. Investigations indicate that microsecond Nd: YAG laser texturing generates well-defined microstructures accompanied by localized thermal effects and a discernible heat-affected zone (HAZ) [22–23]. Furthermore, laser-textured copper alloys undergo wettability aging, transitioning from an initial hydrophilic state to hydrophobicity due to the spontaneous adsorption of atmospheric hydrocarbons onto laser-induced oxide layers [24–25].

Most recent studies have primarily focused on ultrafast (femtosecond or picosecond) laser systems, while comparatively fewer investigations have systematically examined surface modification using Nd: YAG microsecond lasers, which produce distinctive microstructural features and thermal effects [22]. While wettability transitions are widely reported, a direct quantitative correlation between laser parameters, roughness metrics, and wetting behavior remains insufficiently established. In response, this study investigates the surface modification of copper alloys using a microsecond Nd: YAG laser. To systematically address parameter interactions, the Taguchi analytical method is employed to optimize processing conditions and determine the statistical significance of each variable on the resulting surface roughness and contact angle behavior.

Material and methods

1. Material and samples preparation

Commercial-grade copper alloy plates were used as the substrate material in this study. This specific alloy is widely utilized in electrical and electronic applications due to its superior conductivity. Ten square specimens, each with dimensions of 27 × 27 × 0.1 mm, were prepared and subjected to a systematic sequential cleaning procedure. The samples were first ultrasonicated in distilled water for 10 minutes, followed by a 2-minute immersion in acetone to remove organic contaminants, and a final 5-minute rinse in distilled water. The cleaned substrates were then dried at 100°C. The chemical composition of the as-received copper alloy is detailed in Table 1.

Table 1 Chemical composition of copper alloy sample.

Elements Wt. (%)	Cu	Zn	Pb	Sn	P	Mn	Fe	Ni
	98.6	0.098	0.165	0.115	0.0189	0.0155	0.190	0.179
Elements Wt. (%)	Si	Cr	Al	S	As	Ag	Co	Sb
	0.0122	0.0087	0.0241	0.0048	0.0157	0.0081	0.0581	0.0875
Elements Wt. (%)	B	Nb	C	Mg	Zr	Se	Te	Bi
	0.0348	0.0838	0.0500	0.0003	0.00090	0.0123	0.0859	0.0441

Surface texturing was performed using a pulsed Nd: YAG laser system (Model EVCOMPACT 75 D-EVLASER, Italy) operating at a power of 75 W and a wavelength of 1064 nm. The laser was operated in the TEM00 transverse mode with a pulse duration of 9 µs. This Gaussian beam profile ensured high precision during the texturing process. A schematic representation of the experimental setup for the laser surface treatment is illustrated in Figure 1.

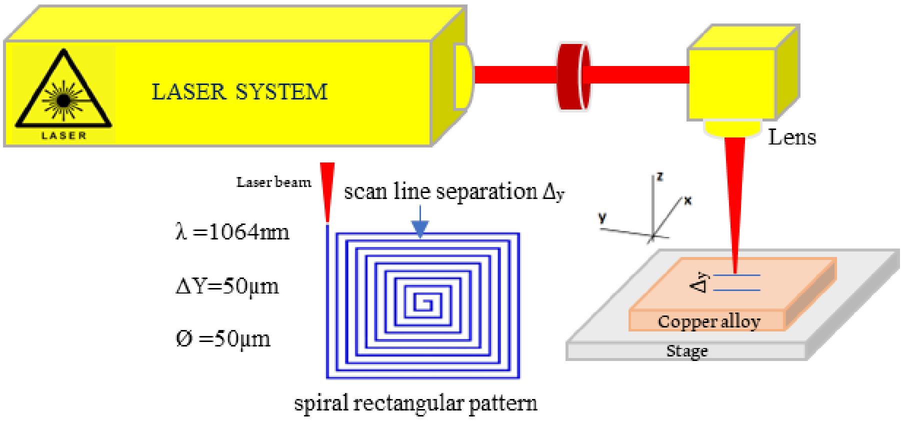

Figure 1: Schematic of the experimental setup for Laser surface texturing (LST) on copper alloy samples.

The influence of three key processing parameters: laser power (10, 20, and 30 W), scanning speed (100, 500, and 1000 mm/s), and pulse repetition rate (10, 20, and 30 kHz) on the surface roughness and wettability was systematically investigated using a Taguchi design of experiments.

2. Wettability measurements

Surface wettability was characterized by measuring the apparent contact angle (APCA) using an automated goniometer (Model 200, Ramé-hart Instrument Co., USA). High-purity distilled water, with a typical resistivity of 18.2 MΩ·cm at 25°C, was used as the probe liquid. To ensure statistical reliability, APCA measurements were performed at four random locations on each sample surface, and the average values were recorded.

3. Surface roughness measurement

The surface topography was characterized using a Time 3221 digital surface roughness tester. The arithmetic average roughness (R_a), representing the absolute vertical deviations of the roughness profile from the mean line, was recorded over a defined evaluation length. To ensure statistical consistency and accuracy, three measurements were performed at different locations on each sample, and the average values were utilized for the subsequent Taguchi analysis.

4. Design of Experiment using Taguchi Method

The Taguchi method is a robust statistical approach used to optimize process parameters and analyze the interactions between controllable factors [26]. This methodology allows for the identification of optimal configurations with a significantly reduced number of experimental runs compared to full-factorial designs. In this study, an L_9 orthogonal array was selected as the design matrix. This approach is highly cost-effective and efficient, as it minimizes experimental error and variability while ensuring that each factor is tested across multiple levels. The orthogonal nature of the L_9 array prevents the impact of confounding variables, providing a clear understanding of the contribution of each laser parameter to the surface properties. The specific experimental layout and factor levels are detailed in Table 2.

Table 2 Taguchi L_9 orthogonal array.

N	Laser power [W]	Scanning speed [mm/s]	Repetition rate [kHz]
0	As received		
1	10	100	10
2	10	500	20
3	10	1000	30
4	20	100	20
5	20	500	30
6	20	1000	10
7	30	100	30
8	30	500	10
9	30	1000	20

Results and discussion

Statistical analysis was performed using Minitab 17 software. The Taguchi method was employed to systematically evaluate the influence of laser processing parameters on each individual response variable. An L_9 orthogonal array was utilized to define the experimental combinations, and the resulting experimental data for contact angle and surface roughness were then processed to determine the statistical significance of each factor.

1. Taguchi Analysis of Contact Angle

The response table for means (Table 3) summarizes the average contact angle values across the three levels of each processing factor. Based on the Delta (Δ) values, the pulse repetition rate was identified as the most significant factor (Rank 1), followed by laser power (Rank 2) and scanning speed (Rank 3). The high Delta value for the repetition rate indicates that it exerts the most substantial influence on the resulting surface energy and wetting behavior. Specifically, the highest average contact angle (100.83°) was achieved at the third level of the repetition rate (30 kHz), demonstrating that higher pulse frequencies promote increased hydrophobicity on the copper surface. The main effects plots for the mean apparent contact angle (APCA) are illustrated in Figure 2.

Table 3 Response Table for Means (Contact Angle ±1.2°).

Level	Laser power [W]	Scanning speed [mm/s]	Repetition rate [kHz]
1	84.09°	94.53°	90.68°
2	94.45°	88.84°	83.54°
3	96.51°	91.69°	100.83°
Delta	12.41	5.70	17.28
Rank	2	3	1

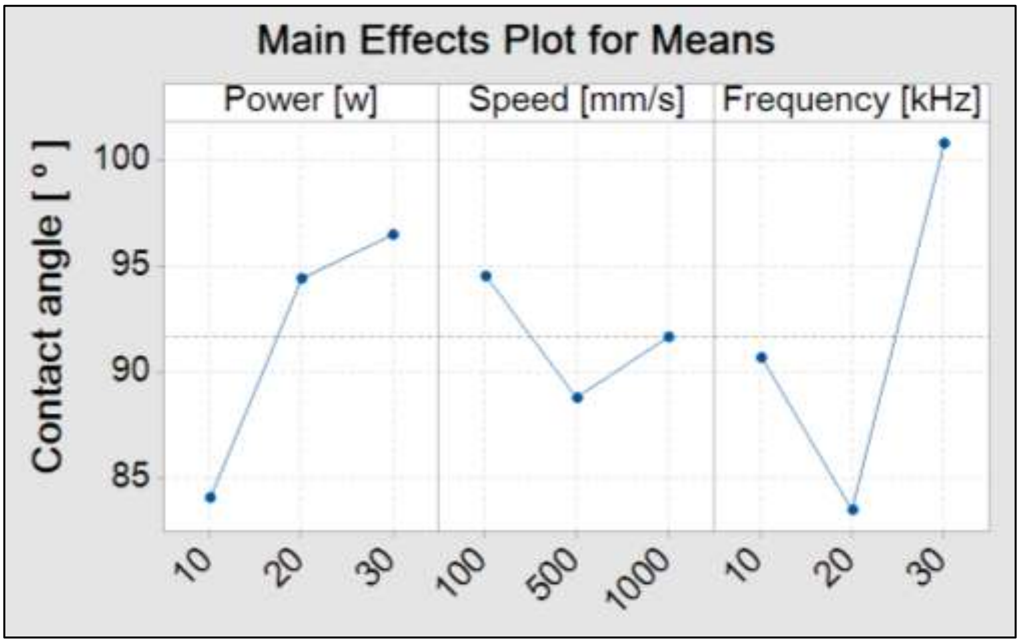

Figure 2: Main effects plots for means of contact angle.

2. Taguchi Analysis of Surface Roughness

The response table for surface roughness (Table 4) indicates that the pulse repetition rate exerted the most dominant influence on the resulting topography. Similar to the wettability results, the highest arithmetic roughness (R_a = 0.2797µm) was recorded at the third level of the repetition rate (30 kHz). While the influences of scanning speed and laser power were less pronounced, they remained comparable to one another in their contribution to surface morphology. This suggests that the increased pulse frequency at 30 kHz leads to a higher degree of material redistribution or thermal accumulation, thereby increasing the vertical deviations of the surface profile. The main effects plots for the mean surface roughness (R_a) are illustrated in Figure 3.

Table 4 Response Table for Means (Surface Roughness ±0.0002 µm).

Level	Laser Power [W]	Scanning speed [mm/s]	Repetition rate [kHz]
1	0.2680	0.2617	0.2737
2	0.2790	0.2747	0.2610
3	0.2673	0.2780	0.2797
Delta	0.0117	0.0163	0.0187
Rank	3	2	1

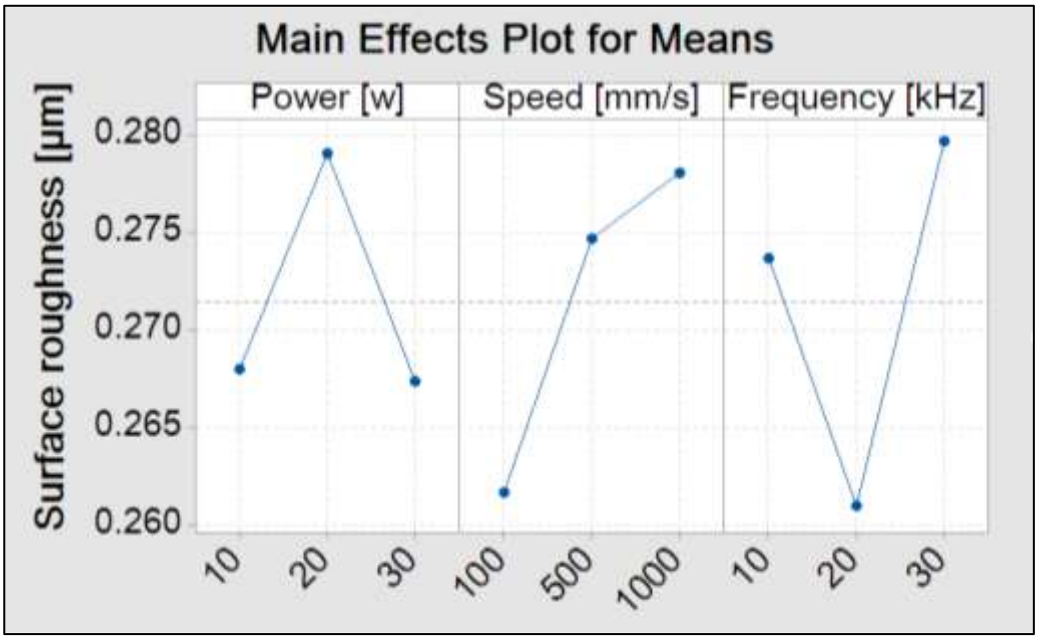

Figure 3: Main effects plots for means of surface roughness.

Our findings demonstrate a transition in the wetting regime, driven by the simultaneous increase in surface roughness (R_a) and contact angle at higher pulse repetition rates. The enhanced hydrophobicity (100.83°) observed at 30 kHz is likely attributed to the formation of a Cassie-Baxter state. In this regime, the laser-induced micro-grooves and increased surface area effectively trap air pockets beneath the droplet. These air pockets minimize the solid-liquid contact area, preventing the water from fully penetrating the surface topography and resulting in a significantly higher apparent contact angle.

Conclusion

This research investigated the influence of laser processing parameters, specifically laser power, scanning speed, and pulse repetition rate, on the surface modification of thin copper alloy substrates using an Nd: YAG laser. Utilizing a Taguchi L_9 orthogonal array, the study systematically evaluated the impact of these factors on surface roughness and wettability. The results demonstrate that the pulse repetition rate is the most critical parameter governing both surface topography and the apparent contact angle. While laser power was found to be the second most influential factor for wettability, scanning speed showed a more pronounced effect on surface roughness.

The study further concludes that the increased roughness at higher repetition rates (30 kHz) promotes a transition toward a Cassie-Baxter wetting state, where trapped air pockets within the laser-induced micro-grooves enhance the hydrophobic character of the copper surface. To further strengthen these findings, future research should explore a broader range of factor levels and incorporate multi-response optimization to achieve a precisely tailored surface functionality.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that they have no conflict of interest.

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